

## REGIONAL AND FEEDSTOCK EFFECTS ON ECONOMICS OF INTEGRATED COAL GASIFICATION/POWER PLANT SYSTEMS

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### INTRODUCTION

Coal's major role in alleviating our energy shortage depends on our ability to derive clean fuels from it. Low and medium Btu gas from coal can be important industrial and utility fuels. We are presenting the results of an investigation into how competitive these coal derived fuels are for power generation. Coal gasifiers integrated with either combined cycle or conventional steam cycle power plants are compared with conventional coal fired power plants with and without flue gas desulfurization (FGD).

The geographical areas selected for study purposes are two National Electric Reliability Council (NERC) Regions--the Chicago area (MAIN Region) and the New England Area (NPCC Region). In the MAIN region, the high sulfur coals studied were Illinois No. 6, an eastern coal, and Rosebud, a western coal. The low sulfur coals studied were Stockton, West Virginia, eastern coal and Wyodak western coal. The same coals were used for the NPCC region except that Middle Kittanning coal was the representative high sulfur eastern coal. The characteristics of coal selected are summarized in Table 1.(1)

### BASIS OF POWER PLANT DESIGN

800 Mw is the base load unit size in this study. Capacity factor is 70%. Coal storage and handling facilities provide capacity for 60 days onsite storage.

For a combined cycle base load unit, the study case plant contained four 200 Mw modules, each consisting of a gas turbine, heat recovery boiler, steam turbine, and generator.

The fixed capital costs for all power plant configurations and fixed operating costs for the two conventional power plant technologies are summarized in Table 2. The fixed operating costs for the integrated cases are discussed in a separate section.

### GASIFIER SELECTION

#### Selection Criteria

Although gasifiers differ in many ways, they are generally classified according to coal flow within the reactor. In a fixed-bed gasifier, the steam required for grate cooling and for preventing clinker formation is greater than the amount of steam required for the gasification reaction, thereby lowering the overall thermal efficiency in gasification. In addition, due to the large coal particle sizes and the moderate temperature involved, the fixed-bed gasification rates are low, and solid residence times of one to two hours are required. These gasifiers, however, have excellent turndown capabilities.

In a fluidized bed, the upward flow of gas is at a velocity slightly above that required to merely support the coal. The relatively short coal residence time (20 to 40 min.) results in a lower operating efficiency than for the fixed bed. Increasing the thermal efficiency requires increasing the coal residence time by using multistage beds to obtain the countercurrent conditions.

TABLE 1. Characteristics of Coals Selected

	High Sulfur Coal			Low Sulfur Coal	
	<u>Illinois No. 6</u>	<u>Rosebud</u>	<u>Mid-Kittanning</u>	<u>Stockton</u>	<u>Wyodak</u>
<u>Proximate Analysis: %</u>					
Moisture	9.7	9.8	3.3	3.0	29.5
Volatile Matter	36.6	35.2	30.1	34.9	30.1
Fixed Carbon	42.2	46.7	57.5	54.3	33.9
Ash	<u>11.5</u>	<u>8.3</u>	<u>9.1</u>	<u>7.8</u>	<u>6.5</u>
Total	100.0	100.0	100.0	100.0	100.0
<u>Ultimate Analysis: %</u>					
Hydrogen	5.3	5.2	5.2	5.2	7.3
Carbon	63.4	60.8	75.3	75.4	45.7
Nitrogen	1.4	0.9	1.3	1.4	1.1
Oxygen	13.9	22.8	6.9	9.6	39.0
Sulfur	4.5	2.0	2.2	0.6	0.4
Ash	<u>11.5</u>	<u>8.3</u>	<u>9.1</u>	<u>7.8</u>	<u>6.5</u>
Total	100.0	100.0	100.0	100.0	100.0
<u>HHV, Btu/lb</u>	11,605	10,379	13,282	13,084	8,167
<u>Ash Fusibility, °F</u>					
Initial	2,330	2,010	2,020	2,910+	2,163
Softening	2,430	2,060	2,080	2,910+	2,223
Fluid	2,590	2,110	2,210	2,910+	2,250

In an entrained bed, the raw coal fed into the unit is transported by the velocity of the gas. The extent of coal conversion to gas is limited by the short solid residence time of less than ten seconds. In order to achieve essentially complete conversion and to maintain high thermal efficiency, a multistage countercurrent unit is desired.

For application to power plants of both conventional and combined cycle type, a gasification process with a high throughput and a high degree of reliability is desirable. Gasifier turndown capability is of less importance for base load units. In a combined cycle, high pressure gasifiers are desirable, whereas low pressure gasifiers are satisfactory for conventional cycles.

A review of gasifier specifications indicates that an entrained-bed gasifier meets the criteria, i.e., pressurized, single stage for combined cycle applications and low pressure, two-stage for conventional cycle power plant applications.

TABLE 2. SUMMARY OF POWER PLANT FIXED CAPITAL AND OPERATING COSTS

BASIS: JANUARY 1977

	MAIN				NPCC			
	HIGH SULFUR COAL		LOW SULFUR COAL		HIGH SULFUR COAL		LOW SULFUR COAL	
	TILL	NO. 6	ROSEBUD	STOCKTON	WYODAK	MID.	ROSEBUD	STOCKTON
FIXED CAPITAL COST: MM\$								
LOW SULFUR W/O FGD	-	-	-	420.4	432.8	-	-	424.6
HIGH SULFUR W/FGD	547.8	547.0	-	-	-	550.8	552.4	-
MED. BTU W/COMB. CYC.	227.4	227.4	227.4	227.4	227.4	229.7	229.7	229.7
LOW BTU W/COMB. CYC.	227.4	227.4	227.4	227.4	227.4	229.7	229.7	229.7
MED BTU W/CONV. CYC.	277.6	277.6	277.6	277.6	277.6	280.4	280.4	280.4
LOW BTU W/CONV. CYC.	280.7	280.7	280.7	280.7	280.7	283.5	283.5	283.5
FIXED OPERATING COST: MM\$/YR								
LOW SULFUR W/O FGD	-	-	-	6.2	6.3	-	-	6.3
HIGH SULFUR W/FGD	20.9	20.9	-	-	-	21.2	21.1	-
								6.4

### Fuel Characteristics

The different gasification processes produce variations in raw or clean gas composition. However, for a given gasification process, experimental data using various coal feeds, ranging from bituminous to lignite, indicate that the characteristics of clean or raw gas composition are almost independent of types of coal employed. For example, the raw gas composition from low pressure two-stage, oxygen-blown, entrained-bed gasifiers does not vary greatly when fed with bituminous, subbituminous or lignite<sup>(2)</sup>. For the present study, therefore, it is assumed that the product gas composition from a selected gasifier is independent of the type of coal feed. Typical fuel characteristics for low and medium Btu gas obtained from an entrained gasifier are presented in Table 3.

### Process Description

Simplified block flow diagrams of the integrated gasification/conventional boiler and combined cycle plants are shown in Figures 1 and 2, respectively. Since the entrained-bed gasifier was selected for the applications of both power plant configurations, the gasification process description presented is valid for both power plant applications.

In the entrained-bed gasifier, prepared, pulverized coal is fed to the gasifier along with steam and oxygen/air. Low pressure steam for the gasifier reaction is produced in the gasifier cooling jacket. Raw gas at 2700°F is usually water quenched and then passed through a waste heat boiler. The gas is cooled in a venturi scrubbing system and sent to a suitable desulfurization system. The clean product gas is then sent to the fuel ports of the steam generator (boiler). A balanced-draft, tangentially-fired, controlled circulation steam generator is used to burn the clean, low or medium Btu gas.

For the combined cycle facility, compressed air and cleaned fuel gas are fired in the combustion chamber of the gas turbine. The hot combustion gases are then expanded through the turbine to generate electrical power. The exhaust from the gas turbine is used further to generate high pressure steam in an unfired boiler before being sent to the stack. The high pressure steam drives the steam turbine to generate additional electric power.

### BASIS OF INTEGRATED GASIFIER/POWER PLANT SYSTEM DESIGN

The performance of various gasifier and gasification system configurations as applied to the production and utilization of low and medium Btu gas was evaluated by examining the effect of gasification parameters on thermal efficiency for a given coal. Subsequently, the effect of varying coal feed on thermal efficiency/performance was estimated based on consideration of key constituents in the coal, i.e., moisture, sulfur, oxygen, and ash.

### Effect of Gasification Parameters on Thermal Efficiency

The gasification parameters affecting thermal efficiency are oxidizing medium (air versus oxygen), pressure, and number of gasifier stages. A gasification system, which utilizes relatively pure oxygen for partial combustion of the coal to supply heat for the endothermic steam-carbon gasification reaction, usually has a higher thermal efficiency than if air were the oxidant. For the pressure effect, as the operating pressure increases, the driving force for the exothermic hydrogen-carbon reaction reduces the amount of oxidation required, thereby increasing the heating value of the gas produced and increasing the thermal efficiency. A two-stage, entrained-bed gasifier can reduce thermal losses by gasifying char produced in the low temperature stage (about 1800° F) in a high temperature stage. The gas from the high temperature stage

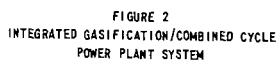
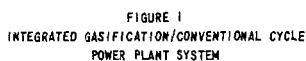


TABLE 3. TYPICAL FUEL CHARACTERISTICS FOR LOW AND MEDIUM-BTU GAS

	<u>Low-Btu Gas</u>		<u>Medium-Btu Gas</u>	
	<u>Low Pressure Entrained Bed</u>	<u>Low Pressure Entrained Bed</u>	<u>Pressurized Entrained Bed</u>	
Clean Gas Composition (% Dry)				
CO	22.24	52.73	29.54	
H <sub>2</sub>	17.18	36.13	32.36	
CO <sub>2</sub>	7.02	10.04	21.67	
CH <sub>4</sub>	0.03	-	15.83	
N <sub>2</sub>	<u>53.53</u>	<u>1.10</u>	<u>0.60</u>	
Total	100.00	100.00	100.00	
HHV: Btu/LB	120-130	280-290	358	
Stoichiometry Combustion Air, Lb/LB Fuel	1.05	3.03	4.02	

provides the heat for the coal feed stage. The two-stage, entrained-bed gasifier thus avoids the high coal combustion requirement that a single-stage, entrained-bed gasifier has (2700° to 3300° F).

Performance data for the gasification systems considered for power generation are presented in Table 4. The tabulation represents a combination of published data and engineering judgement applied in accordance with the effective system parameters outlined above. The hot and cold gas efficiencies for low pressure, single-stage, oxygen-blown, entrained-bed gasifiers<sup>(3)</sup> (Case 3) and the low pressure, two-stage, air-blown, entrained-bed gasifier<sup>(4)</sup> (Case 4) were obtained from published data. The efficiencies for Cases 1 and 2 were determined by taking into account pressure effects, i.e., increase of the thermal efficiencies by 1% for high pressure operation.

For producing electricity, when gasifiers are integrated with either a conventional or combined cycle power plant, the net station system efficiency is higher than the cold low or medium Btu gas efficiency but lower than the hot gas efficiency. Auxiliary power produced in the power plant and sensible heat recovered during the gas cleanup can be used as a part of the gasification system energy requirement. In general, integrating a gasification system with a power plant, will improve the efficiency of heat recovery and provide opportunities to optimize the overall cycle.

Integration of gasifiers with the combined cycle plant provides higher gasifier system efficiency than those with conventional power plants because of increased potential for cycle optimization. Additionally, for integration with the same power plant configuration, medium Btu gas provides a higher gasifier system efficiency than low Btu gas.

Table 4. Thermal Efficiency Of Gasification Systems

Case	Med.-Btu Integ. w/Base C.C.	Low-Btu Integ. w/Base C.C.	Med.-Btu Integ. w/Conv. Base	Low-Btu Integ. w/Conv. Base
	1	2	3	4
Type Gasifier	Pressurized Entrained Single Stage	Pressurized Entrained Two Stage	L.P. Entrained Single Stage	L.P. Entrained Two Stage
Oxidant	O <sub>2</sub>	Air	O <sub>2</sub>	Air
Coal Type	Ill. 6 Bit.	Ky. Bit.	Ill. 6 Bit.	Ky. Bit.
Gasifier Eff.				
Hot Gas, % (a)	92	93	91	92
Cold Gas, % (b)	76	77	75	76
Gasif. System Eff.%(c)	84.0	81.5	80.0	77.5
Power Plant Eff.%(c)				
Conventional Cycle	N/A	N/A	36.0	36.0
Combined Cycle	38.5	38.5	N/A	N/A
Integrated Gasifier/ Power Plant Eff., %(d)	32.3	31.4	28.8	27.9

(a) Hot gas efficiency,

$$\% = \frac{\text{HHV of gas @ gasifier exit temp.} + \text{sensible heat @ gasifier exit temp.}}{\text{HHV of coal fed to gasifier}} \times 100.$$

(b) Cold gas efficiency,

$$\% = \frac{\text{HHV of gas (after tar, oil, NH}_3\text{, H}_2\text{S have been removed)}}{\text{HHV of coal fed to gasifier}} \times 100.$$

(c) GAI estimate.

(d) Product of gasifier system efficiency and power plant efficiency.

In determining overall plant efficiencies for all the integrated cases, power plant efficiencies of 36.0% and 38.5% were used for conventional and combined cycle power plants, respectively.

#### Effect of Coal Feed on Thermal Efficiency

In order to facilitate an economic evaluation of alternatives, it was necessary to determine the effect of coal feed variation on the thermal efficiencies of the gasification systems and overall plants.

The key constituents of coal, which were considered in estimating the thermal efficiencies of a given process when fed with alternative coals, are moisture, sulfur, oxygen and ash.

- a. Moisture - Coal must be dry to about 3% moisture. The effect of moisture on gasifier system efficiency was determined by using a heat requirement of 1,000 Btu per pound of moisture.
- b. Sulfur - The gasifier system efficiency increases with decreasing sulfur content of coal. The effect of sulfur on efficiency was estimated by using the heating value of elemental sulfur.
- c. Oxygen - Highly reactive coals can be gasified at relatively lower temperatures than coals of low oxygen content. The low gasifier temperature requires less carbon combustion and increases thermal efficiency.
- d. Ash - As the ash content of coal increases, the amount of energy required in the coal preparation section for the dryer and pulverizer increases. Additionally, the energy losses in the gasifier system also increase with increasing ash content because increased power is required to feed the coal and some sensible heat is lost with ash leaving the gasifier.

The overall effect on thermal efficiency of these coal constituents was established for each coal in the study as a variance from the efficiency of the base coal. Typical results for variations in the gasifier system efficiencies from the based coal are summarized in Table 5.

#### ECONOMICS OF INTEGRATED SYSTEMS

##### Fixed Capital and Operating Costs

The base, fixed capital costs for all four integrated cases were estimated by adjusting published data<sup>(5)</sup> to establish compatibility between the performance as proposed in the reference and that required to produce a desired fuel. The base, fixed operation and maintenance labor cost was estimated from a Combustion Engineering study<sup>(4)</sup>. The published data was adjusted using a power factor on electric generation capacity from a Fluor-Utah study<sup>(6)</sup>. The estimated base, fixed capital and operating costs are summarized in Table 6.

After the fixed capital and operating costs of each gasification system for base coals were established, the costs of each system when fed with alternative coals were determined using the calculated coal fuel rates, regional factors, and the scale factors required to adjust each cost element to compensate for the alternate coal feed. The fixed capital and operating costs for all cases considered are tabulated in Table 7.



TABLE 5. GASIFICATION SYSTEM  
EFFICIENCIES FOR ALTERNATIVE COALS

	<u>BASE COAL</u>	<u>ILLINOIS NO. 6</u>	<u>ROSEBUD</u>	<u>MIDDLE KITTANING</u>	<u>STOCKTON</u>	<u>WYODAK</u>
Medium-Btu Gas Integrated With Combined Cycle	84.0 (Illinois 6)	84.0	84.0	88.0	90.0	84.0
Low-Btu Gas Integrated With Combined Cycle	81.5 (Kentucky 9)	81.5	83.5	85.5	87.5	81.5
Medium-Btu Gas Integrated With Conventional Cycle	80.0 (Illinois 6)	80.0	82.0	84.0	86.0	80.0
Low-Btu Gas Integrated With Conventional Cycle	77.5 (Kentucky 9)	77.5	79.5	81.5	83.5	77.5

TABLE 6. Summary of Low and Medium-Btu Gas Performance and Cost Data For Base Cases  
Base Year: January - 1977

Case	1	2	3	4
Gasifier Type Selected	Medium-Btu Integrated w/Base C.C.	Low-Btu Integrated w/Base C.C.	Medium-Btu Integrated w/Conv. Base	Low-Btu Integrated w/Conv. Base
Region	MAIN	ECAR	MAIN	ECAR
Plant Capacity				
Net MWe	800	800	800	800
Gross MWe	810	810	827	831
Coal Type	Ill. 6 Bit.	Ky. Bit.	Ill. 6 Bit.	Ky. Bit.
As Received %				
Moisture	9.82	10.0	9.82	10.0
Carbon	64.16	63.4	64.16	63.4
Hydrogen	4.25	4.3	4.25	4.3
Nitrogen	1.42	1.4	1.42	1.4
Sulfur	3.35	3.2	3.35	3.2
Oxygen	5.36	6.8	5.36	6.8
Ash	11.64	10.9	11.64	10.9
Heating Value, Btu/Lb	11,390	11,400	11,390	11,400
Efficiencies, %				
Hot Gas(a)	92.0	93.0	91.0	92.0
Cold Gas(b)	76.0	77.0	75.0	76.0
Gasification System(c)	84.0	81.5	80.0	77.5
Overall Plant(d)	32.3	31.4	28.8	27.9
Coal Throughput, TPD	8,906	9,153	9,988	10,301
Fixed Capital Cost: MM\$				
Coal Preparation	21.72	22.15	23.53	24.04
Gasifier + Heat Recovery	54.01	73.26	70.22	95.43
Gas Purification	46.60	77.22	60.64	100.66
Sulfur Recovery	2.69	2.70	3.00	3.00
Oxygen Plant	36.34	-	39.38	-
Gasification Facility	33.72	30.35	36.54	32.88

TABLE 6. (Continued)

	Medium-Btu Integrated w/Base C.C.	Low-Btu Integrated w/Base C.C.	Medium-Btu Integrated w/Conv. Base	Low-Btu Integrated w/Conv. Base
Gasification Utility	50.60	45.55	54.83	49.35
Power Plant	227.40	236.41	277.60	291.80
Liquid Storage (Redundancy)	5.41	5.41	5.41	5.41
Gasif. Plant Land + Site Imp.	3.10	4.21	4.04	5.47
Total Fixed Capital Cost	481.61	497.26	575.19	608.04
Fixed Operating Cost: MM\$/Yr.				
Utility & Material	10.79	11.46	12.82	13.55
O&M Labor	3.83	3.83	3.40	3.40
General Overhead	7.73	7.84	9.18	9.70
Total Fixed Operating Cost	22.35	23.13	25.40	26.65

(a) Hot Gas Eff. % =  $\frac{(\text{HHV of gas} + \text{sensible heat}) @ \text{gasifier exit temp.}}{\text{HHV of coal fed to gasifier}}$

(b) Cold Gas Eff. % =  $\frac{\text{HHV of gas (after H}_2\text{S, COS, NH}_3, \text{ tar removal)}}{\text{HHV of coal fed to gasifier}}$

(c) GAI estimate (see Table 5).

(d) Multiplication of gasification system efficiency with power plant efficiencies of 38.5% for combined cycle plant and 36.0% for conventional plant (see Table 5).

TABLE 7. SUMMARY OF FIXED CAPITAL AND OPERATING COSTS FOR ALTERNATE COALS

BASIS: JANUARY, 1977 PRICING

FIXED CAPITAL COST: MM\$	MAIN				NPCC			
	ILLINOIS		HIGH SULFUR COAL		MIDDLE		HIGH SULFUR COAL	
	NO. 6		ROSEBUD		KITTANING		ROSEBUD	
	STOCKTON		WYODAK		STOCKTON		WYODAK	
MED-BTU W/COMB. CYCLE	479.6	493.4	418.9	469.4	461.0	498.3	423.1	474.1
LOW-BTU W/COMB. CYCLE	468.6	479.2	387.3	433.8	450.2	484.2	391.3	438.3
MED-BTU W/CONV. CYCLE	574.1	589.3	499.8	555.8	55.28	595.2	504.8	561.4
LOW-BTU W/CONV. CYCLE	573.8	588.8	472.2	526.6	551.6	594.7	476.9	531.6
FIXED OPER. COST: MM\$/YR								
MED-BTU W/COMB. CYCLE	22.3	22.6	19.8	21.9	21.6	22.8	20.1	22.1
LOW-BTU W/COMB. CYCLE	22.2	22.5	18.8	20.7	21.5	22.8	19.0	20.9
MED-BTU W/CONV. CYCLE	25.3	26.1	22.3	24.6	24.4	26.4	22.5	24.8
LOW-BTU W/CONV. CYCLE	26.3	27.1	22.1	24.3	25.4	27.4	22.3	24.6

TABLE 8. Financial Parameters Used to  
Develop Power Generation Cost

Plant Life	20 Years
Depreciation (Based on Total Capital Less Working Capital)	5%/Year Straight Line
Fraction Debt	0.75
Return on Equity	15%/Year
Interest on Debt	12%/Year
Load Factor	70%
Working Capital	Coal Inventory for 60 Days and 1% of Fixed Capital Cost
Interest During Construction	Interest on Debt x Total Fixed Capital x 2
Federal Income Tax Rate	48%

#### Development of Power Generation Cost

The fixed capital and operating costs summarized in Tables 2 and 7 were used to develop power generation cost; the utility financing method was used with the financial parameters summarized in Table 8. The power generation costs calculated are summarized in Table 9 together with the delivered coal cost.

#### CONCLUSIONS

Referring to Table 9, the following conclusions were observed:

1. The western coals (both high and low sulfur) in the load center sites of the NPCC region are not competitive with eastern coals, whereas the western coals are competitive with the eastern coals in the MAIN region.
2. In the MAIN region, both eastern and western high sulfur coals are competitive with low sulfur coals. In the NPCC region, however, the eastern high sulfur coal appears to be more attractive than the eastern low sulfur coals.
3. Integrated conventional plants in both regions for all coals are not competitive with the two conventional power plants using high sulfur coal with FGD and low sulfur without FGD.
4. Integrated combined cycle plants using the eastern high sulfur coal in the NPCC region are more attractive than the two conventional power plants.
5. In the MAIN region, the integrated combined cycle plants are either better than or comparable to the high sulfur coal fired plants with FGD, whereas they are not competitive with the low sulfur coal fired plants without FGD.

TABLE 2. SUMMARY OF POWER GENERATION COST

BASIS: JAN-1977 ¢/KWH

NERC REGION HIGH OR LOW SULFUR COAL BED	MAIN				NPCC			
	HIGH SULF. ILL. 6	ROSEB.	STOCKT.	LOW SULF. WYOD.	HIGH SULF. M-KIT.	ROSEB.	STOCKT.	LOW SULF. WYOD.
COAL COST, \$/TON DELIVERED FOB MINE	24.81 19.55	20.95 9.22	39.48 31.97	18.92 7.19	27.37 21.08	27.42 9.22	39.13 31.97	25.38 7.19
LOW SULFUR COAL WITHOUT FGD	-	-	3.065	2.751	-	-	3.067	3.171
HIGH SULFUR COAL WITH FGD	3.340	3.276	-	-	3.316	3.616	-	-
MED-BTU GAS INT. W/COMB. CYCLE	3.202	3.163	3.310	3.256	3.031	3.512	3.317	3.702
LOW-BTU GAS INT. W/COMB. CYCLE	3.197	3.147	3.230	3.149	3.026	3.508	3.233	3.606
MED-BTU GAS INT. W/CONV. CYCLE	3.718	3.684	3.811	3.751	3.524	4.077	3.817	4.251
LOW-BTU GAS INT. W/CONV. CYCLE	3.779	3.740	3.766	3.691	3.577	4.145	3.770	4.208

All observations were based on the fixed delivered coal cost. In order to determine coal cost situations where the integrated combined cycle plants in the MAIN region would be competitive with low sulfur conventional coal fired plants without FGD, the sensitivity of the integrated of the plant generation cost to coal cost is analyzed, as shown in Figure 3. The lowest power generation cost in the main region was 2.751¢ per kilowatt hour for Wyodak coal without FGD. Figure 3 indicates that for medium Btu gas integrated with a combined cycle power plant, the delivered coal prices would have to be \$15.00, \$12.50 & \$25.00 per ton of Illinois No. 6, Rosebud, and Stockton coals respectively to be competitive with the Wyodak coal fired without FGD. The study was intended solely to demonstrate how the selection of coal feedstocks and regions effect the power generation costs for various configurations.

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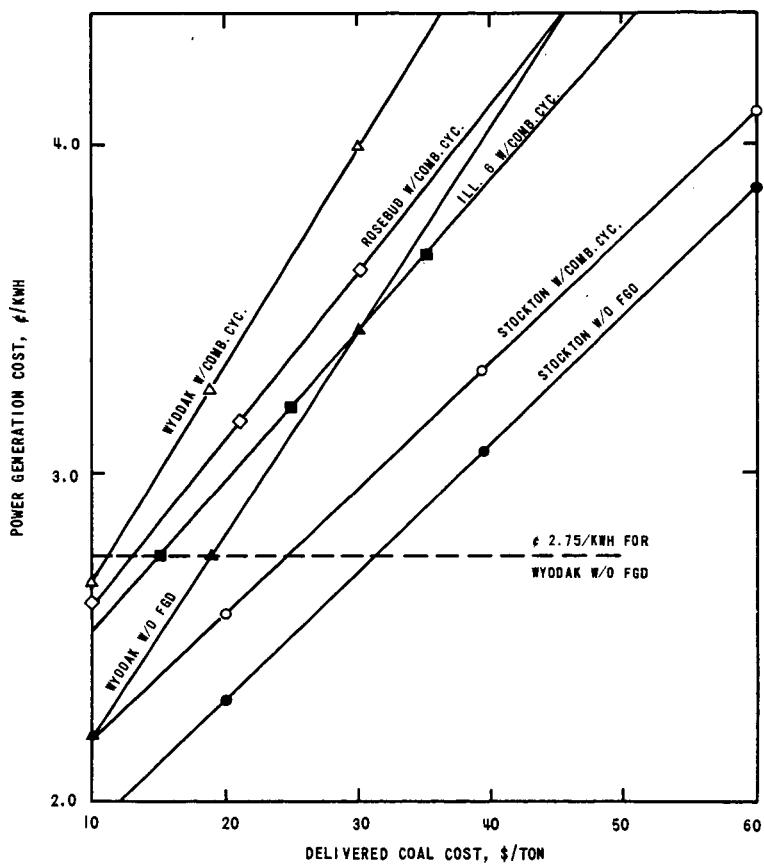


FIGURE 3  
SENSITIVITY OF POWER GENERATION  
COST TO DELIVERED COAL COST